US Department of Energy
Cooperative Agreement Number:
DE FC02-01CH11079

ADVANCED RECIPROCATING ENGINE SYSTEMS

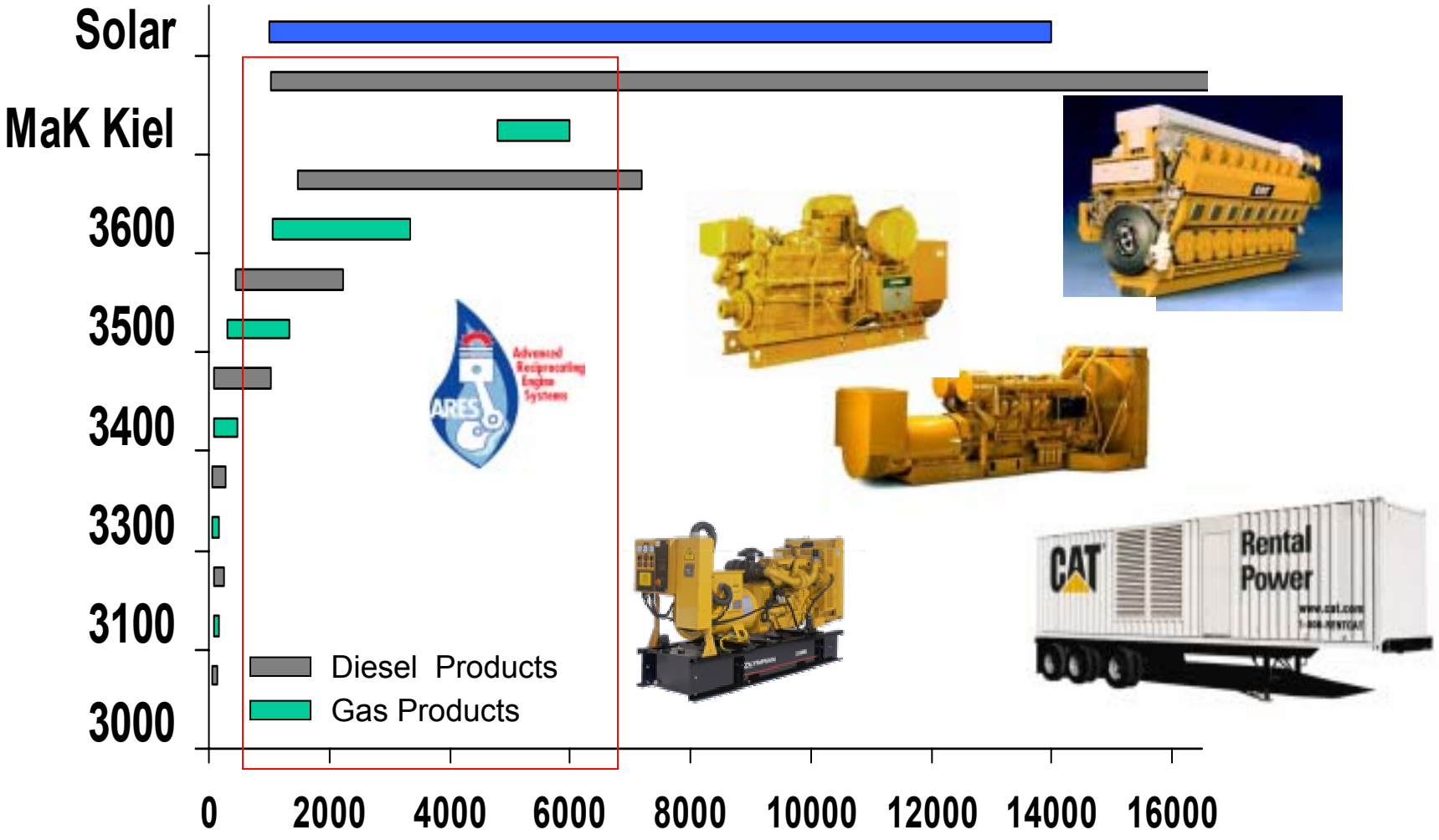
Peer Review **April 23-24, 2002**

Gordon Gerber **Principal Investigator - Caterpillar**

Contents:

- Caterpillar Power Products
- ARES Program Overview
- ARES Team Approach
- Efficiency and Emissions Directions
- Phases and Tasks
  - Phase I Approach / Milestones
  - Phase II Approach / Milestones
  - Phase III Approach / Milestones
- Program Risks / Opportunities
- Summary and Near Term Plan

Caterpillar Power Products

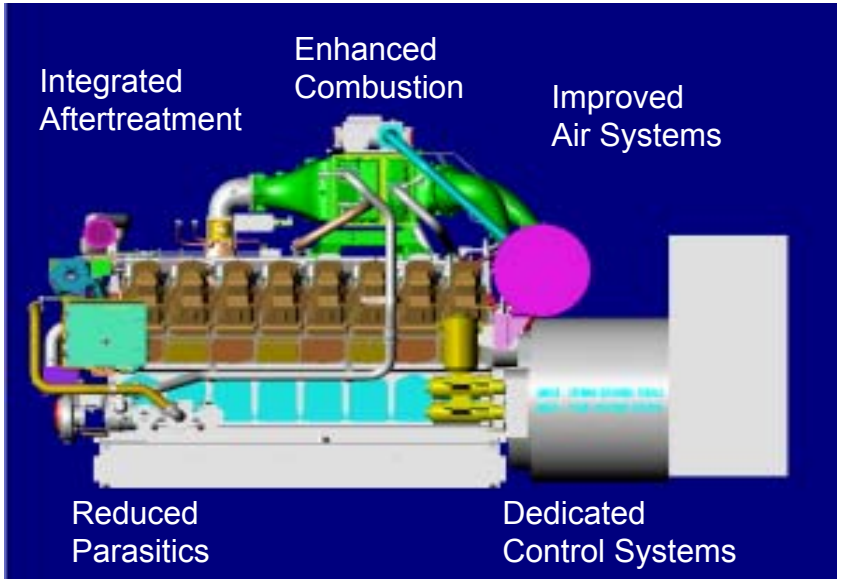


ARES Program Overview

Objective:

By 2010, create a natural gas powered reciprocating engine system with the following attributes:

- 50% thermal efficiency
- 0.1 gram/bhp-hr NOx or less
- 10% reduction in first cost / ekw
- No loss of reliability or availability



5 Basic Development Areas

Approach:

Phased Introduction

I 44% Efficiency
0.50 g/bhp-hr NOx
2004 Intro

II 47% Efficiency
0.1 g/bhp-hr NOx
2007 Intro

III 50% Efficiency
<0.1g/bhp-hr NOx
2010 Intro

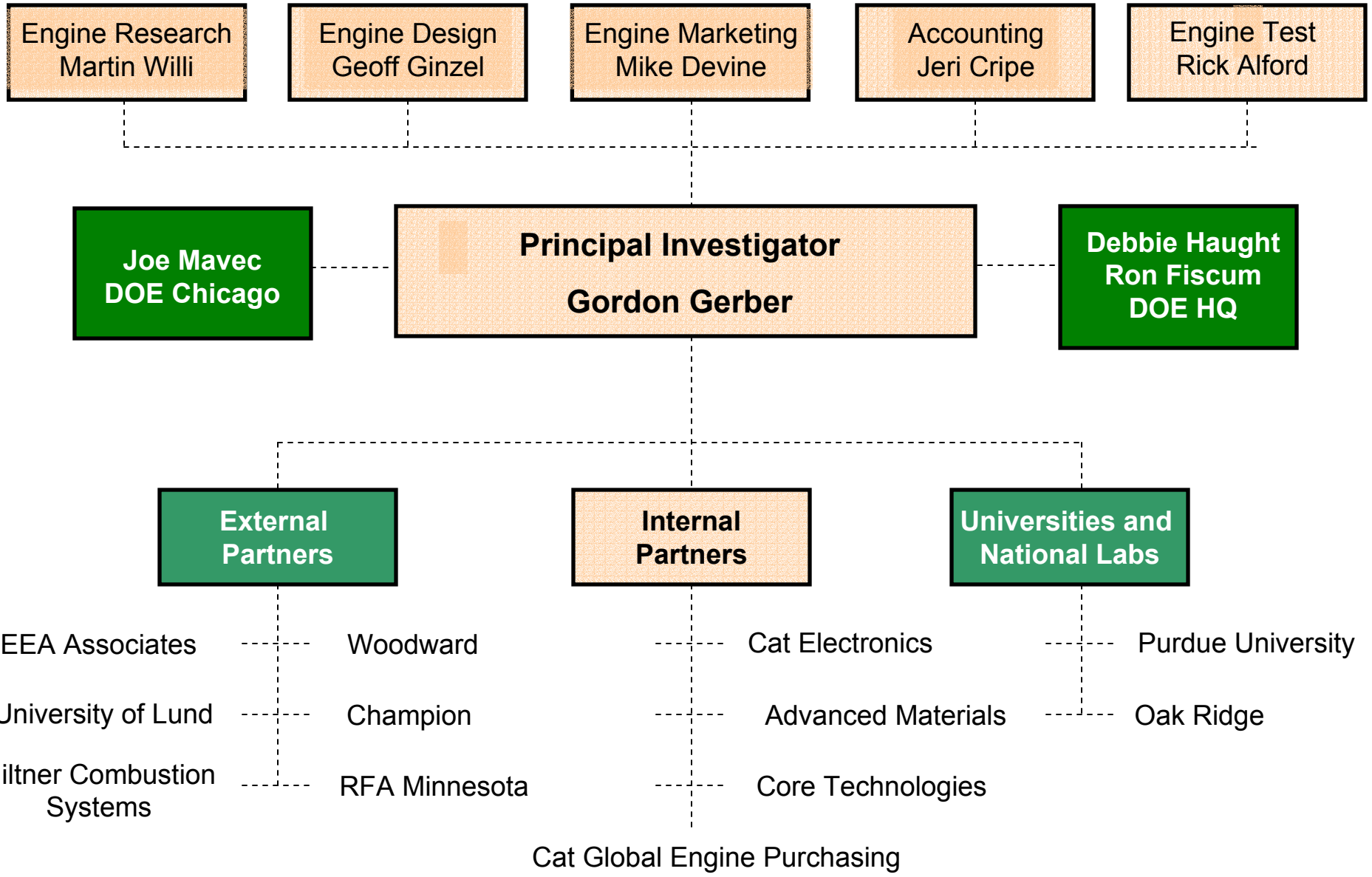
Program Budget

Required $70M+
Allocated $17.2M

Task Description

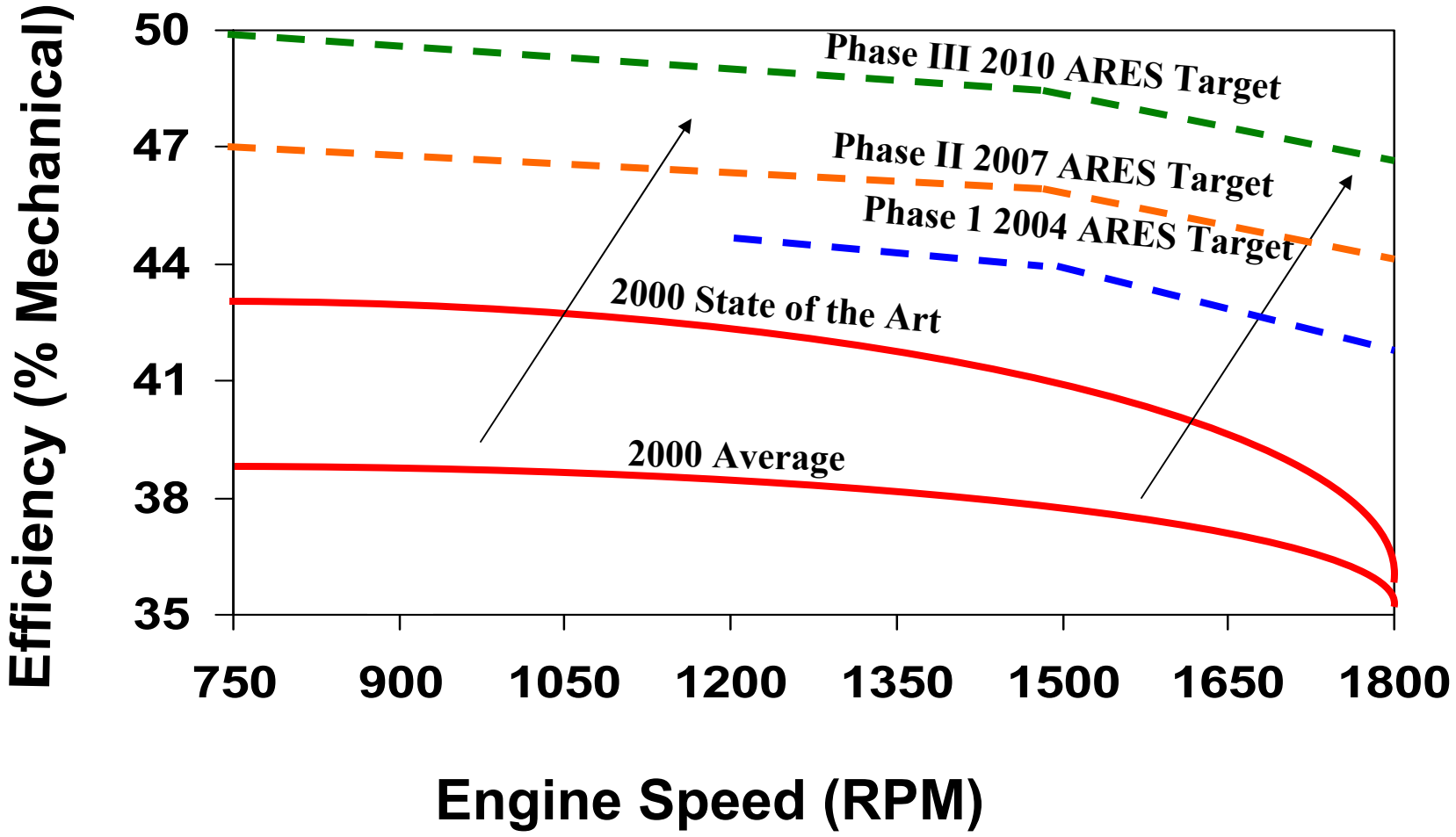
		Phase I	Phase II	Phase III
Task 1	Component Development / Test	Underway	Underway	Underway
Task 2	Systems Development / Test	Underway		
Task 3	Engine Integration / Prep	Planned		
Task 4	Engine Build / Lab Test	Planned		
Task 5	Pre-Commercial Demonstration			

ARES Team Approach

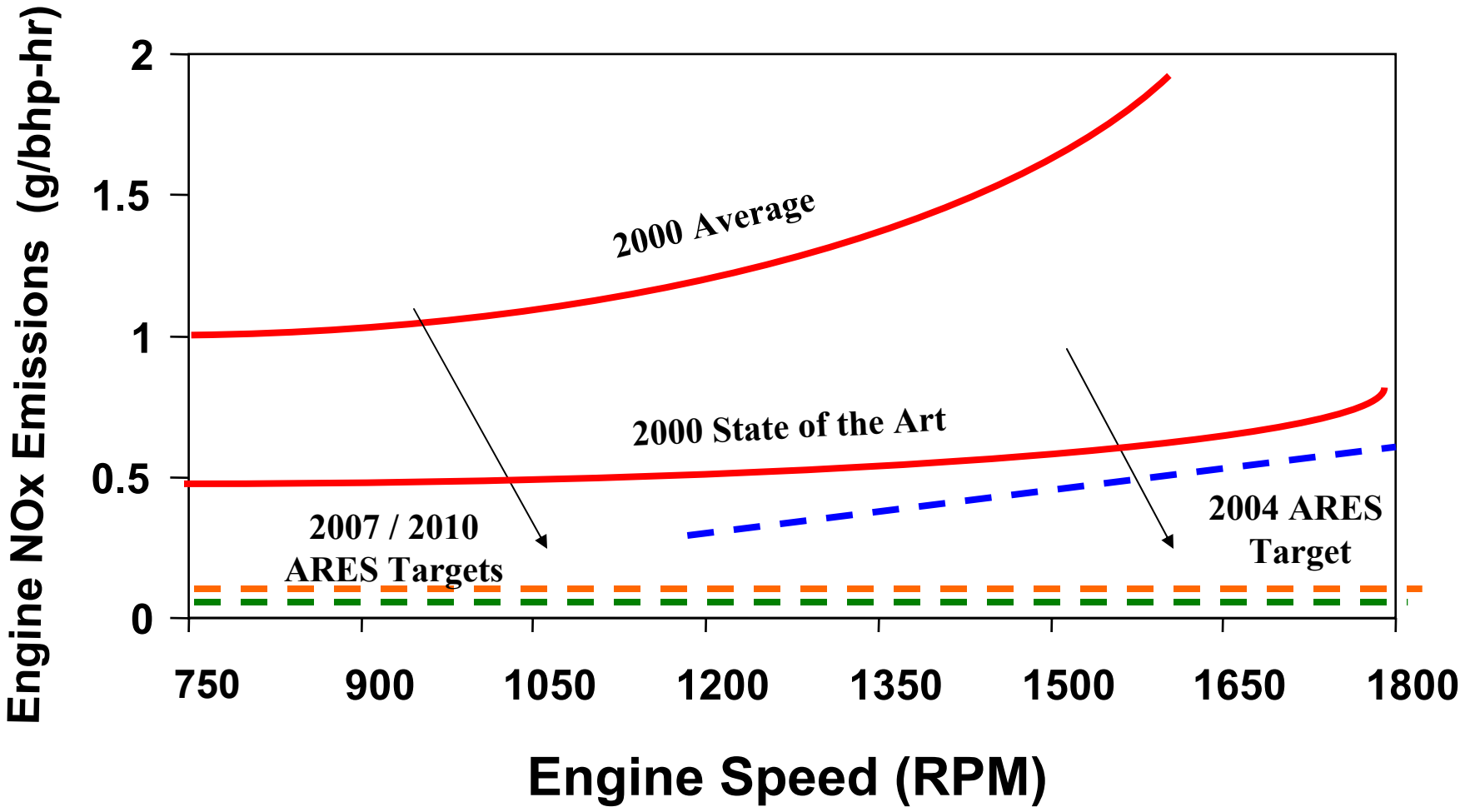


CAT Electric Power

Efficiency Direction



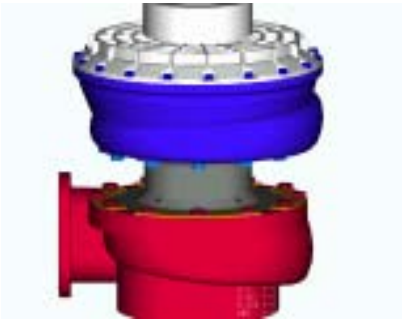
NOx Emissions Direction



Phase I Approach
44% Efficiency at 0.50 g/bhp-hr NOx

Prime Path Technologies:

- **Combustion:**
  - Lean burn open chamber
  - Stoichiometric - EGR – 3 way catalyst (SE-3)
  - Prechamber micropilot
- **Air Systems:**
  - Increased pressure single stage turbocharging
  - High efficiency turbocharger
- **Friction Reduction:**
  - New centerline design with low friction camshaft systems
  - Low friction ring packages
  - Improved efficiency pumps
- **Controls:**
  - Caterpillar in-cylinder air/fuel ratio control
  - New electronic controls platform
- **Aftertreatment:**
  - Engine out standard (0.25 –1.0 g/bhp-hr)
  - SCR or SE-3 for lower requirements



HEAT™ Turbo Concepts
Patents Pending

Phase I Milestones
44% Efficiency at 0.50 g/bhp-hr NOx

Main Task	Milestone
Program Planning	Schedule High Level Plan
Air System Concept Design	Design / Analyze Increased Pressure Ratio Turbo
Market Study Completion	Analyze market trends and ARES participation
Single Cyl Test Engine Design	Design basic single cylinder test engine
Single Cyl Test Engine Build	Procure and Build single cylinder test engine
Basic cycle simulation model	Complete initial cycle simulation model
→ Single Cyl Test Engine Operation	Startup testing of the single cylinder test engine
SE-3* Concept Evaluation	Fully evaluate SE-3* concepts
Reformed Fuel Concepts	Fully evaluate reformed fuel (H_2) concepts
Multi-cylinder design	Design the multi-cylinder ARES engine platform
Multi-cylinder build	Build the multi-cylinder ARES engine platform
Multi-cylinder tests	Test the multi-cylinder ARES engine platform
Prototype Evaluation	Field test the first multi-cylinder ARES engine platform
Pre-Production Evaluation	Complete ARES engine pre-production validations
Market Launch	Launch the ARES engine for full production
Production	Initial shipments of the Phase 1 ARES engines

* Stoichiometric – EGR - Three Way Catalyst

Key Technology Focus 1
SE-3* Concept Evaluation

Statement of Work

Develop a stoichiometric combustion concept utilizing EGR and a passive 3-way catalyst for low NOx emissions (< 0.1 g/bhp-hr) while simultaneously reducing CO and non-methane HC's to low levels.

Technical Approach

- Single cylinder performance testing from lean burn through SE-3 operation.
- Single cylinder catalyst out performance testing

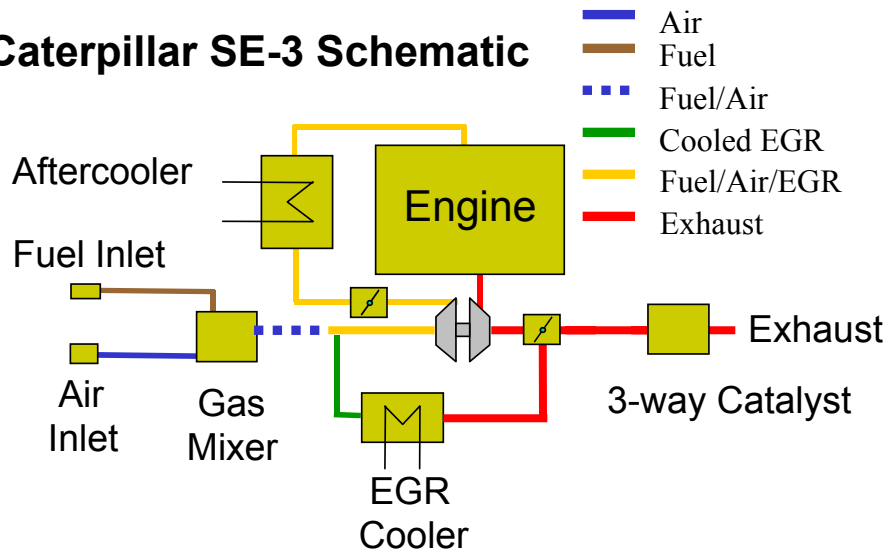
Key Results to Date

- Performance tests at increased loads to simulate a multicylinder engine at stoichiometric operation.
- Lean burn to SE-3 testing completed for validation of SE-3 combustion model

Challenges and Next Steps

- Catalyst out testing on 3501 Single Cylinder.
- SE-3 combustion modeling for engine configuration optimization

Caterpillar SE-3 Schematic



* Stoichiometric - EGR - Three Way Catalyst

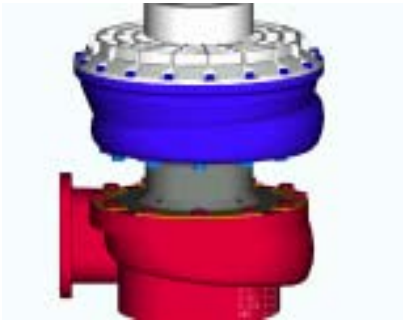
Key Technology Focus 2
HEAT® Turbocharger

Statement of Work

Develop an increased pressure ratio turbo design with improved efficiencies to meet the increases in airflow required for ARES power and emissions goals

Technical Approach

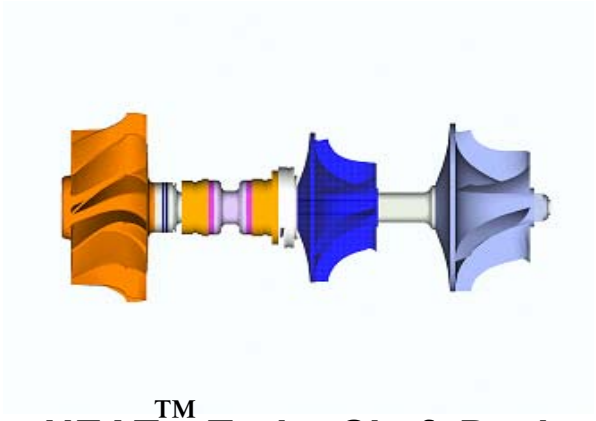
- Integrate two stages of compression on a single shaft
- Integrate a high efficiency intercooler in the compressor hsg.
- Develop a bearing system that is stable at all conditions



HEAT™ Turbo Concepts
Patents Pending

Key Results to Date

- Analysis work complete
- Concept designs underway
- Procurement of initial test hardware



HEAT™ Turbo Shaft Design

Challenges and Next Steps

- Complete Procurement and operate in bench test mode.
- Apply this concept when needed into ARES engine development

* **H**igh **E**fficiency **A**dvanced **T**urbocharger

CAT Electric Power

Key Technology Focus 3
Single Cylinder Test Bed

Statement of Work

Design, procure, build, and test a single cylinder test engine that incorporates state of the art components adaptable for future ARES technologies.

Technical Approach

- Concept a new single cylinder test engine for use in ARES program phased testing
- Design, procure, and build this engine based on program technical requirements.

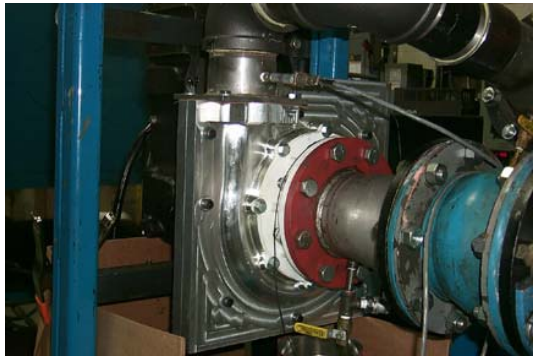
Key Results to Date

- Concept design and components procured
- Initial engine build is complete
- Test cell renovation and engine installation underway

Challenges and Next Steps

- Installation and debug of a new engine concept
- Integrating test results into computational modeling

Single Cylinder Test Engine



ARES Coolant Pump Bench Test

Phase II Approach
47% Efficiency at 0.10 g/bhp-hr NOx

Prime Path Options:

- **Combustion Options**:

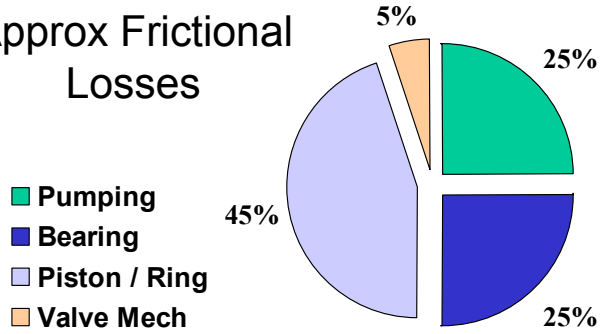
HCCI	None required
SE-3	Passive three way catalyst
Reformed fuel open chamber	None required
Prechamber with lube oil micropilot	Advanced SCR
Dual fuel concepts	To be determined
Lean burn with miller cycle	Advanced SCR

- **NOx Aftertreatment Options**

- **Friction Reduction Options:**
  Roller element bearings, friction coatings,
  thin rail oil rings, low friction bearing systems

-**Control System Options:**
  Cylinder pressure based algorithms
  Direct NOx and fuel input sensors
  New generation control platforms
  Integrated aftertreatment controls
  Multistrike rotating ignition concepts

Approx Frictional Losses



- **Air System Options:**
  HEAT™ turbo / turbocompounding / miller cycle / tuned intake and exhaust manifolds

Phase II Milestones
47% Efficiency at 0.10 g/bhp-hr NOx

Main Task	Milestone
Program Planning	Outline a High Level Plan
Phase II Basic Research	HCCI*, SE-3 Testing
Redesign Air System Concepts	Define air system options
Control System definition	Define best control system options
Market Study Validation	Validate market trends and ARES participation
Update Single Cyl Test Engine Design	Update with Phase II concepts
Update Single Cyl Test Engine Build	Build Phase II single cylinder test engine
Update Basic cycle simulation model	Complete improved cycle simulation model
Single Cyl Test Engine Operation	Startup testing of the Phase II SCTE
Phase II SE-3 Concept Evaluation	Fully evaluate SE-3 in a Phase II configuration
Phase II HCCI Concept Evaluation	Fully evaluate HCCI in a Phase II configuration
Reformed Fuel Definition	Fully evaluate reformed fuel operation in Phase II
Other Design Integration	Incorporate other designs to be defined
Update Multi-cylinder design	Update Phase I muiticylinder ARES engine to Phase II
Update Multi-cylinder build / Test	Test the Phase II multicylinder ARES engine platform
Prototype Evaluation	Field test the Phase II multicylinder ARES engine
Pre-Production Evaluation	Complete Phase II engine pre-production validations
Market Launch	Launch the Phase II ARES engine for full production
Production	Initial shipments of the Phase II ARES engines

* Homogeneous Charged Compression Ignition

Phase III Approach
50% Efficiency at <0.10 g/bhp-hr NOx

Prime Path Options:

Combustion Options	NOx Aftertreatment Options
Open Chamber HCCI	None Required
Reformed Fuel Open Chamber	None Required
Reformed Fuel Prechamber	Advanced SCR
Dual fuel combustion	To be determined

Friction Reduction:

Camless engine concept

Controls:

Integrated Aftertreatment Controls
Increased BMEP ignition systems
Rail / plasma / corona ignition

Air Systems:

HEAT™ Turbo
Turbocompounding
Miller cycle
Insulated combustion / manifolding

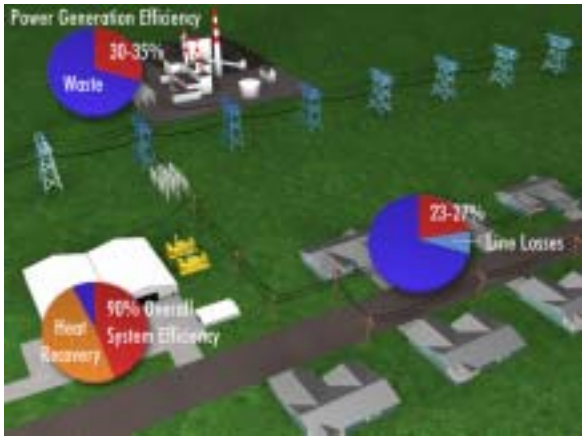
Phase III Milestones
50% Efficiency at <0.10 g/bhp-hr NOx

Main Task	Milestone
Program Planning	Outline a High Level Plan
Phase III Basic Research	HCCI Testing
Redesign Air System Concepts	Define air system options
Redesign Combustion Concepts	Define combustion options
Market Study Validation	Validate market trends and ARES participation
Update Single Cyl Test Engine Design	Update with Phase III concepts
Update Single Cyl Test Engine Build	Build Phase III single cylinder test engine
Single Cyl Test Engine Operation	Startup testing of the Phase III SCTE
Reformed Fuel Definition	Fully evaluate reformed fuel operation in Phase II
Ignition System Definition	Define best ignition system options
Other Design Integration	Incorporate other designs to be defined
Update Multi-cylinder design	Update muiticylinder ARES engine to Phase III
Update Multi-cylinder build / Test	Test the Phase III multicylinder ARES engine
Prototype Evaluation	Field test the Phase III multicylinder ARES engine
Pre-Production Evaluation	Complete Phase III engine pre-production validations
Market Launch	Launch the Phase III ARES engine for full production
Production	Initial shipments of the Phase III ARES engines

Program Risks and Opportunities

Significant Risks:

- Distributed Generation / CHP Markets develop slowly
- Overall program funding limits technology pace
- Material / Thermal Barrier technology has minimal impact
- Technical Path advancement rate slows



Significant Opportunities:

- Market opportunity expansion well beyond 10GW in 2010
- Global emissions reductions via recognition of DER and CHP benefits
- Lower life cycle cost alternatives via ARES packages
- Alternative fuels development as the market expands
- Leveraged technologies to diesel platforms, and applications beyond electric power

Summary and Near Term Plan

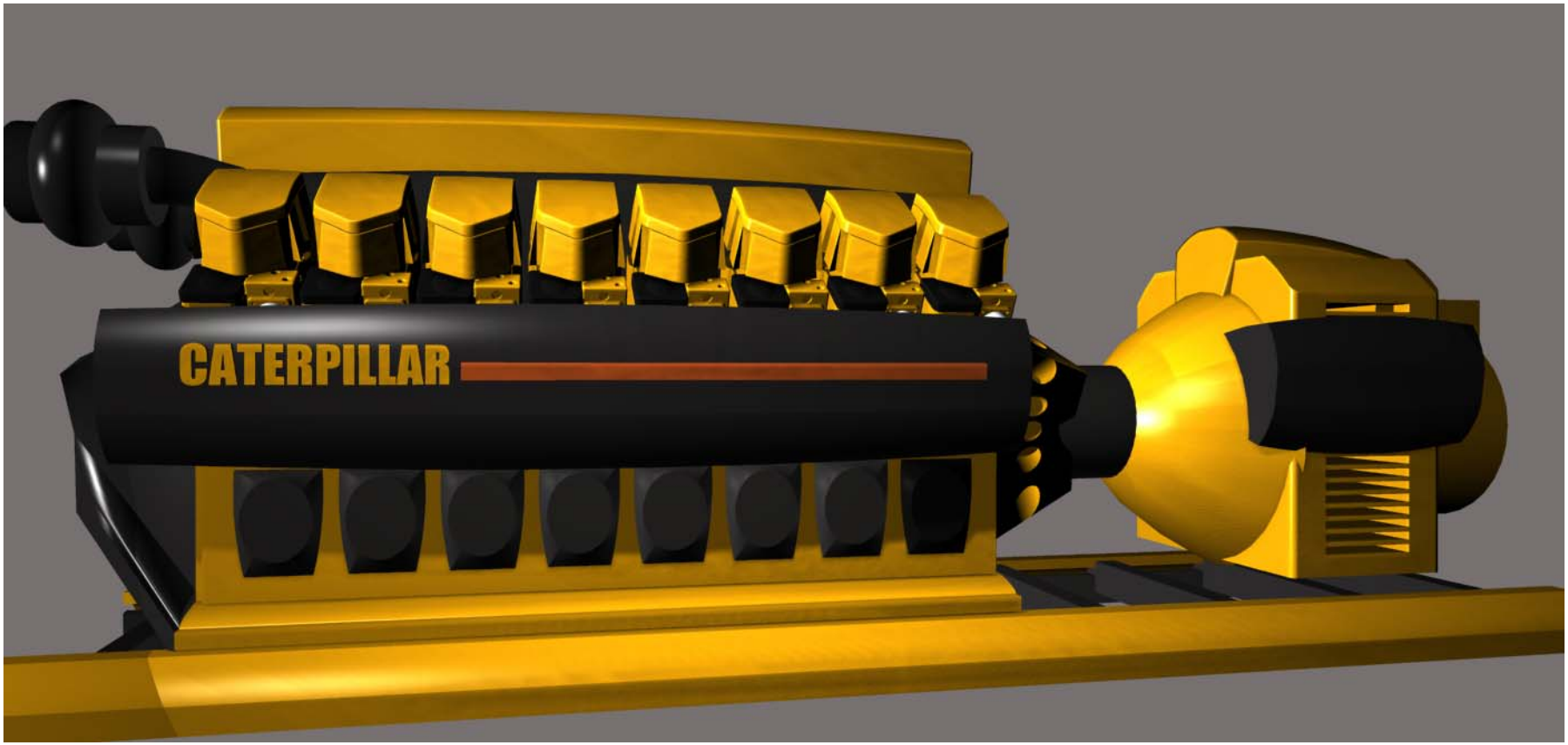
Summary:

- Program planning and initial concept development underway
- Several technical paths pursued towards Phase I goals
- Single cylinder ARES test engine built and being prepped for test
- Phase II and III research underway to reach longer term goals

Next Steps:

- Execute the program plan to realize Phase I goals
- Develop options for Phase II and Phase III goals
- Work closely with the DOE and partners to commercialize each phase

CAT® Electric Power



QUESTIONS ?

ARES Advanced Reciprocating Engine Systems